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Explicit pionic degrees of freedom in deuteron photodisintegration in the Δ -resonance region ^{*} [†]

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Photodisintegration of the deuteron above π -threshold is studied in a coupled channel approach including $N\Delta$ - and πd -channels with pion retardation in potentials and exchange currents.

1. Introduction

Photodisintegration of the deuteron in the Δ -resonance region is particularly interesting in order to investigate the $N\Delta$ -interaction. None of the models developed so far is able to describe in a satisfactory manner the experimental data over the whole Δ -resonance region (for a review see [1]). Among the most sophisticated approaches are the unitary three-body model of Tanabe and Ohta [2] and the coupled channel approach (CC) of Wilhelm and Arenhövel [3]. In both models, all free parameters were fixed in advance by fitting NN - and πN -scattering, and π -photoproduction on the nucleon. Consequently, no adjustable parameters remained for deuteron photodisintegration. However, it turned out that both approaches considerably underestimated the total cross section in the Δ -region by about 20-30% [2,3]. Another failure was the wrong shape of the differential cross section and the photon asymmetry, especially at photon energies above 300 MeV [2-4].

In these calculations, one of the principal problems is the question of how to fix the $\gamma N\Delta$ -coupling $G_{\Delta N}^{M1}(E_\Delta)$ in the $M1$ $N\Delta$ -current

$$\vec{j}_{\Delta N}^{M1}(E_\Delta, \vec{k}) = \frac{G_{\Delta N}^{M1}(E_\Delta)}{2M} \tau_{\Delta N,0} i \vec{\sigma}_{\Delta N} \times \vec{k}, \quad (1)$$

where E_Δ is the energy available for the internal excitation of the Δ and \vec{k} the momentum of the incoming photon. Wilhelm et al. as well as Tanabe et al. have determined $G_{\Delta N}^{M1}(E_\Delta)$ by fitting the $M_{1+}(3/2)$ -multipole of pion photoproduction on the nucleon. The full pion production amplitude $t_{\pi\gamma}(E_\Delta)$ in the $(3,3)$ -channel can be written as

$$t_{\pi\gamma}(E_\Delta) = t_{\pi\gamma}^B(E_\Delta) - \frac{v_\Delta^\dagger \vec{\epsilon} \cdot \vec{j}_{\Delta N}^{M1}(E_\Delta, \vec{k})}{E_\Delta - M_\Delta^0 - \Sigma_\Delta(E_\Delta)}, \quad (2)$$

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[†]Contribution to Few-Body XV, Groningen (1997)

where $t_{\pi\gamma}^B(E_\Delta)$ is the nonresonant Born amplitude. While in [3] an effective $\gamma N\Delta$ -coupling $G_{\Delta N}^{M1}(E_\Delta)$ and the model of [5] for the bare Δ -mass M_Δ^0 , the Δ -self energy $\Sigma_\Delta(E_\Delta)$ and the $\Delta\pi N$ -vertex v_Δ^\dagger has been used, we follow here the work of Tanabe and Ohta (model A in [6]). $G_{\Delta N}^{M1}(E_\Delta)$ contains besides the bare $\gamma N\Delta$ -coupling the contributions from nonresonant pion rescattering (Fig. 1), so that it becomes complex and energy dependent.

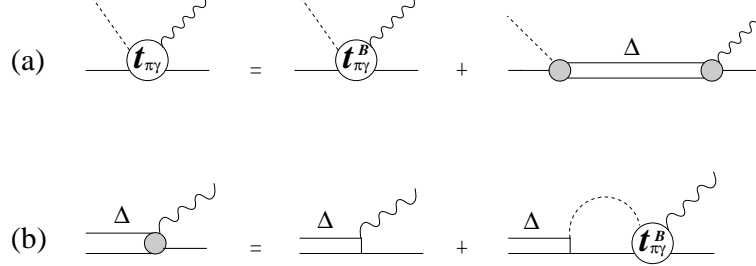


Figure 1. (a) The $M_{1+}(\frac{3}{2})$ -multipole amplitude of pion photoproduction consisting of a Born and a resonant amplitude. (b) The dressed $\gamma N\Delta$ -coupling, including nonresonant pion rescattering.

The Born terms contributing to the $(3,3)$ -channel are the crossed N -pole and π -pole graphs. When embedded into the two-nucleon system, these Born terms become part of the two-body recoil and the π -meson currents, respectively (Fig. 2).

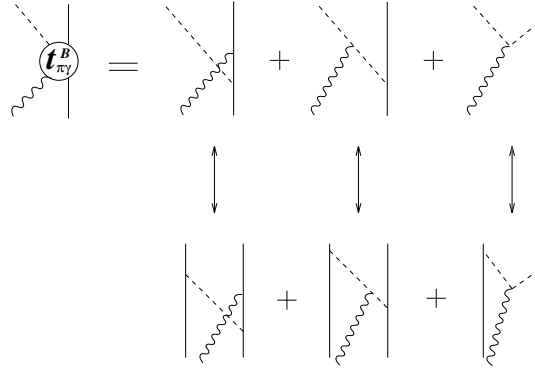


Figure 2. The Born terms contributing to the $M_{1+}(\frac{3}{2})$ -multipole amplitude of pion photoproduction (upper part) and their correspondence in the two-body recoil and meson currents (lower part).

In static calculations, however, the recoil current is not present due to its cancellation against the wave function renormalization current [7]. A similar, but less serious problem arises in the treatment of the pion pole diagrams compared to the meson current of static MEC. It had already been conjectured in [3] that this inconsistent treatment of pion exchange may lead to the observed underestimation of the total cross section in their coupled channel approach, because by incorporating the Born terms effectively into

an increased $M1$ Δ -excitation strength, a satisfactory agreement with the data could be achieved. In order to avoid these shortcomings, we have included for the first time in a coupled channel approach complete retardation in the π -exchange contributions to potentials and MECs.

2. The Model

Concerning the potential models which enter our coupled channel approach, we have chosen for the retarded NN-potential an improved version of the energy dependent Bonn-OBEPT developed by Elster et al. [8], which has to be renormalized via subtraction of a $N\Delta$ -box graph [5]. Transitions between NN - and $N\Delta$ -space are mediated by retarded π - and ρ -exchange whose form factors are fixed by fitting the 1D_2 NN -partial wave. In order to ensure unitarity up to the 2π -threshold, we consider in addition the formation of an intermediate NN -state with the quantum numbers of the deuteron and a pion as spectator (denoted for simplicity by πd -channel).

Concerning the e.m. part of our model, the Δ -excitation is the most important photoabsorption mechanism above π -threshold. It is described by the current operator in Eq. (1) neglecting small E2 contributions. Concerning gauge invariance, we are able to show that current conservation for the π -retarded MECs is fulfilled if we consider besides the usual vertex-, meson- and contact-MECs the recoil current, the recoil and additional two-body charge densities (Fig. 3).

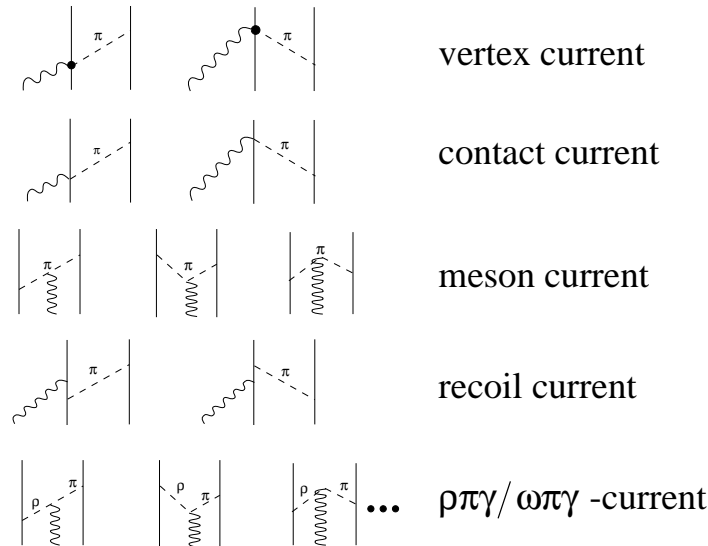


Figure 3. Graphical representation of the retarded π -MECs.

Whereas the effect of the additional two-body charge terms is very small, the recoil contributions turn out to be quite important (see discussion below). They do not appear in static approaches due to their cancellation against the wave function renormalization contributions [7], which have their origin in the renormalization of the baryonic states

when eliminating the mesonic wave function components. This concept breaks down beyond the π -threshold if full π -retardation is considered since the πNN -component can be on-shell. Therefore, we do not orthonormalize and no wave function renormalization contributions appear. Consequently, the recoil current and charge densities have to be included. Because the pion production model of Tanabe and Ohta [6] effectively incorporates ω -exchange, we include in addition the leading order $\rho\pi\gamma$ - and $\omega\pi\gamma$ -currents, which are purely transverse [9]. Because the ρ -mass is rather large, retardation in the ρ -MEC is expected to be rather unimportant and therefore not considered in this work.

3. Results

Our results for the total photodisintegration cross section are shown in Fig. 4. Similar to [3], the static calculation considerably underestimates the data. Inclusion of retardation in the hadronic interaction even lowers further the cross section, which is more than compensated by retardation in the π -MEC leading to a strong enhancement which can be traced back essentially to the inclusion of recoil contributions. The inclusion of the πd -channel and the $\rho\pi\gamma/\omega\pi\gamma$ -MECs enhances the cross section further so that our full calculation now gives quite a good agreement with experimental data over the whole energy range. In Figs. 5 and 6, we show differential cross sections and photon asymmetries for various energies. Whereas the differential cross section is in satisfactory agreement with the data, we slightly underestimate the absolute size of the asymmetry. However, in contrast to [2,3] we are able to reproduce quite well the shape of these two observables at higher energies.

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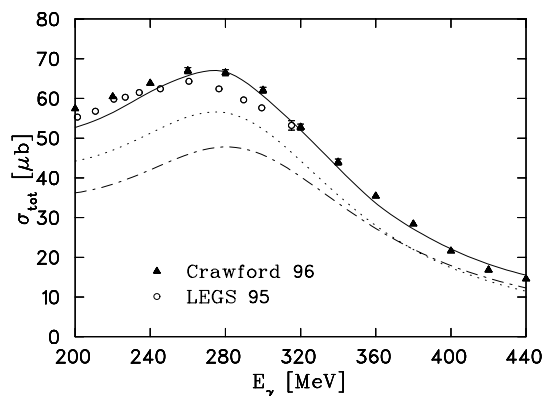


Figure 4. Total cross section for $\gamma d \rightarrow pn$ as a function of photon laboratory energy E_γ in comparison with experiment [4,10]. Dotted: static OBEPR-calculation, dash-dot: retardation switched on only in the hadronic part but static MECs, full: calculation with complete retardation, πd -channel and $\rho\pi\gamma/\omega\pi\gamma$ -MECs.

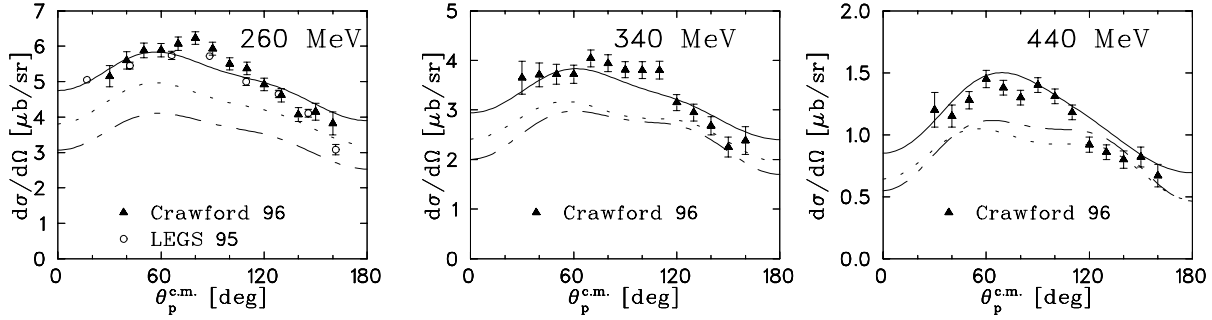


Figure 5. Differential cross section for various energies in comparison with experiment [4,10]. Notation of the curves as in Fig. 4.

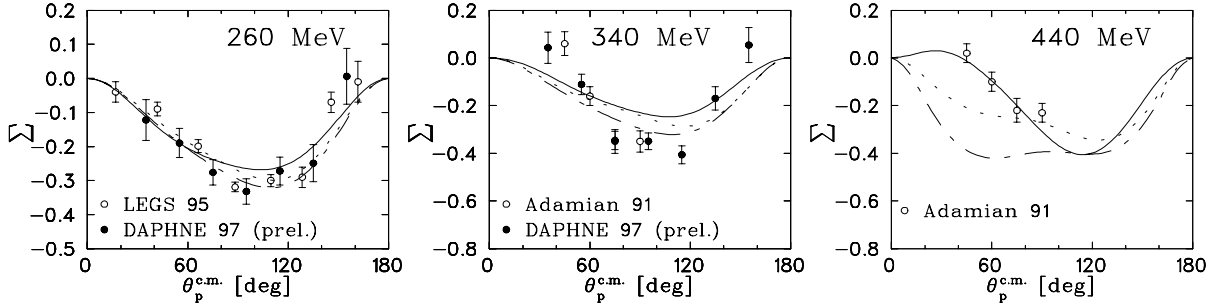


Figure 6. Photon asymmetry Σ for various energies in comparison with experiment [4,11, 12]. Notation of the curves as in Fig. 4.

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